Dynamics and Gravitational Waves from Black Hole Binaries

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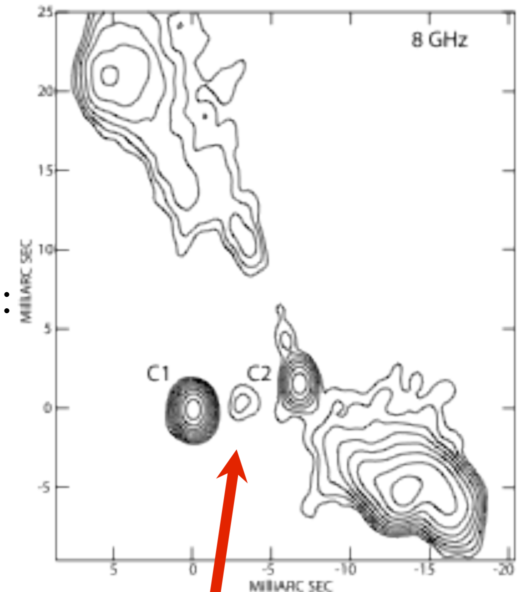
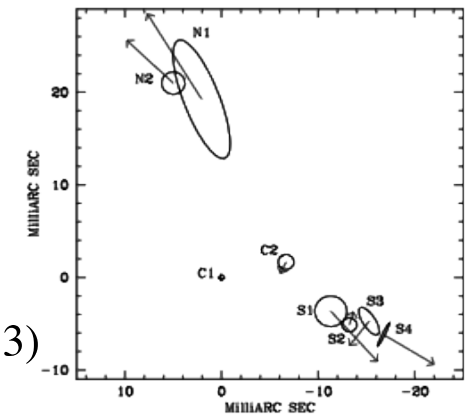
Evidence of Binary Black Holes so far …

But, BBH are much harder to "see". Few observations of close merging pairs so far …



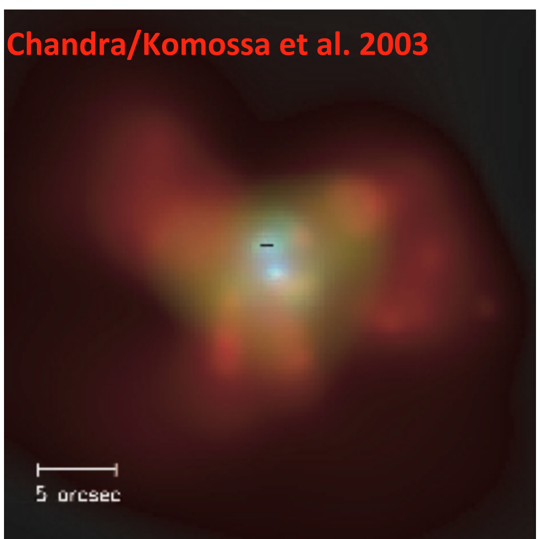
0402+379: (Xu et al. 1994, Maness et al. 2004, Rodriguez et al. 2006):

- Radio observation
- **Separation = 5 pc**



NGC 6240: (Komossa et al. 2003)

- Optical ID: (Fried & Schulz 1983)
- **Separation = 0.5 kpc**



Weakly Emitting Gravitational Waves

SDSS J153636.22+044127.0

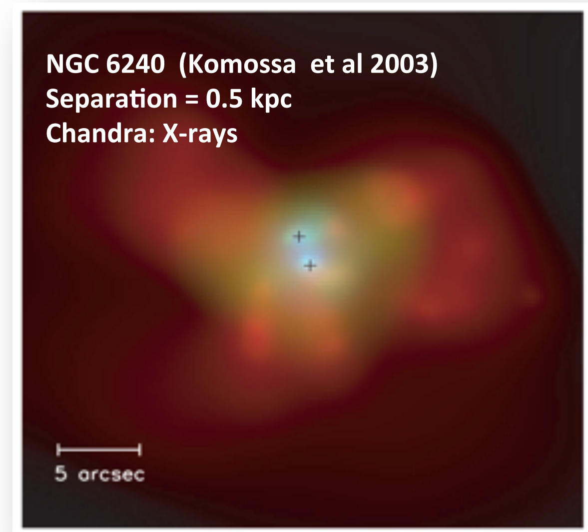
(Lauer & Boroson 2009)

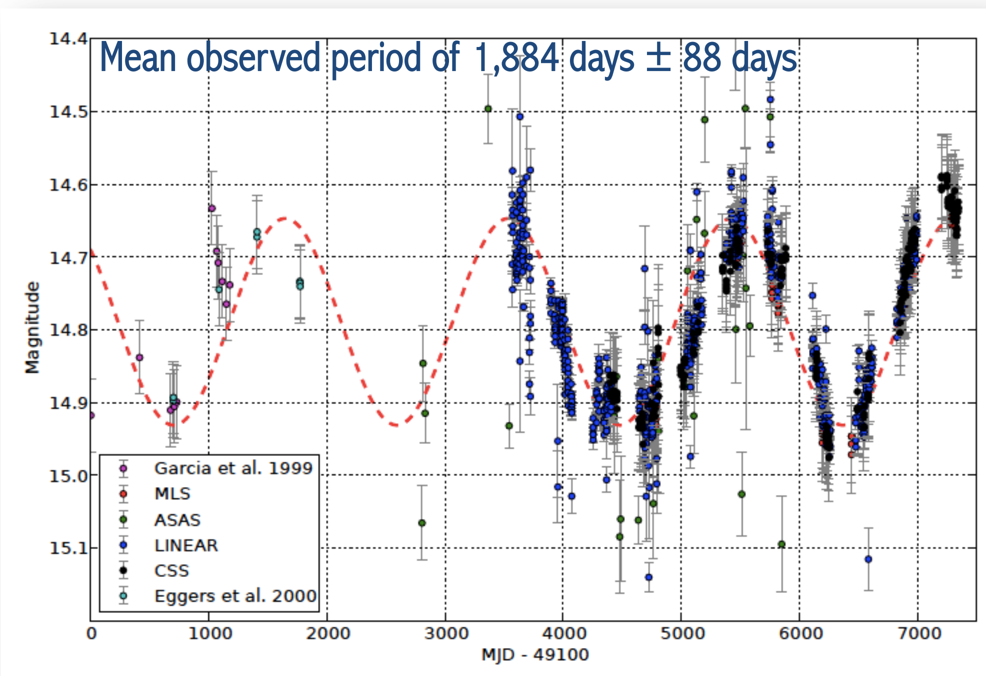
Separation = 0.1pc

1pc = 1 parsec = 3.26 light-years
= 1.9 x 10^{13} miles

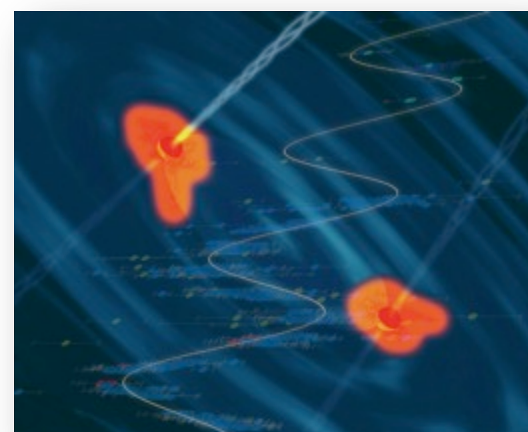
But what about Binary Black Holes ?

- Hierarchical build-up of galaxies from smaller structures (Λ CDM) → galaxies merger → dual black hole systems
- Few observations of resolved subkpc dual nuclei …
- Torques from gas, stellar dynamical friction, gravitational slingshot bring the pair to sub-pc scales in the GW regime (separation <0.1pc)

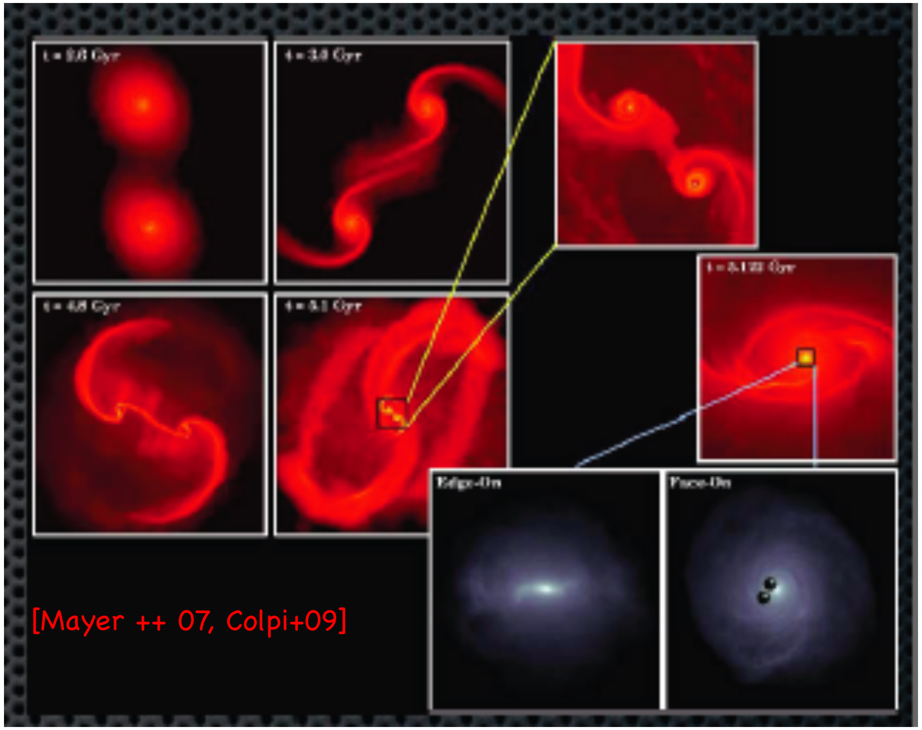




Quasars variability from Catalina Real-time Transient Survey (CRTS) → PG 1302-102 (Graham et al Nature 2015)



Binary Black Hole Mergers

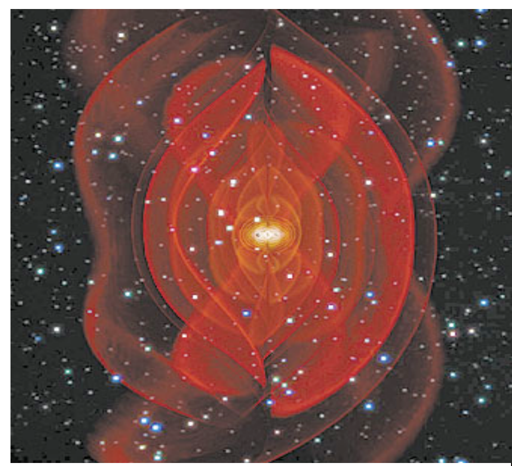


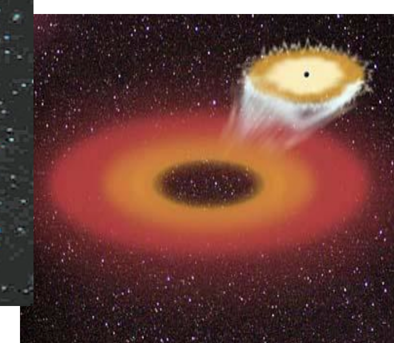
There is strong combined observational/ theoretical support for this scenario:

- Hierarchical build-up of galaxies from smaller structures (ΛCDM) ⇒ galaxies merger ⇒ BBH mergers
- Stellar dynamical friction, torques from gas, gravitational slingshot bring the pair to sub-pc scales …

The general relativistic merger:

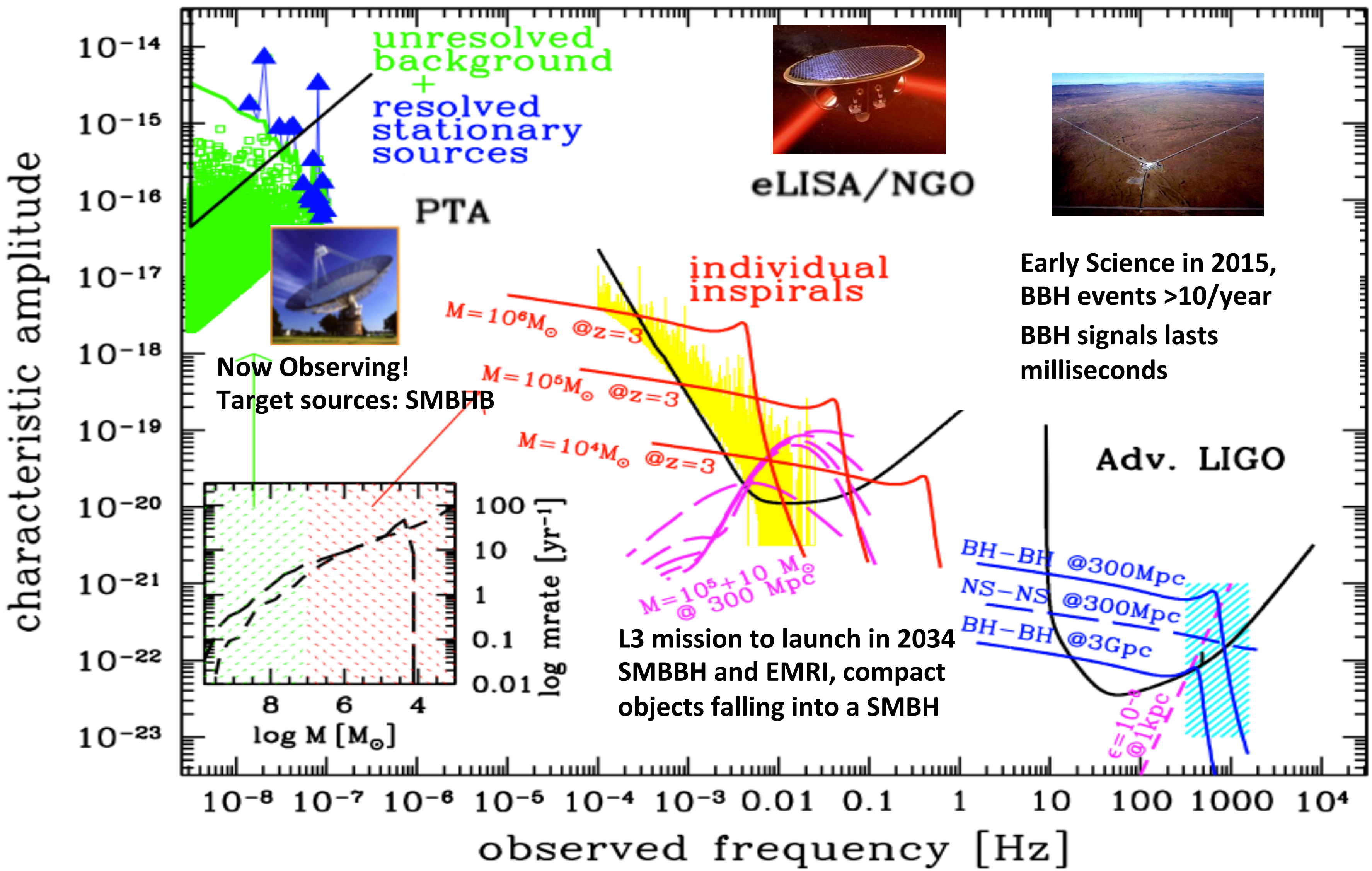
- **GW** emission (3-10% of the total mass) drive the binary to the final merger
- The BH remnant will **recoil** from its host structure, depending on the BH spins and masses at merger.



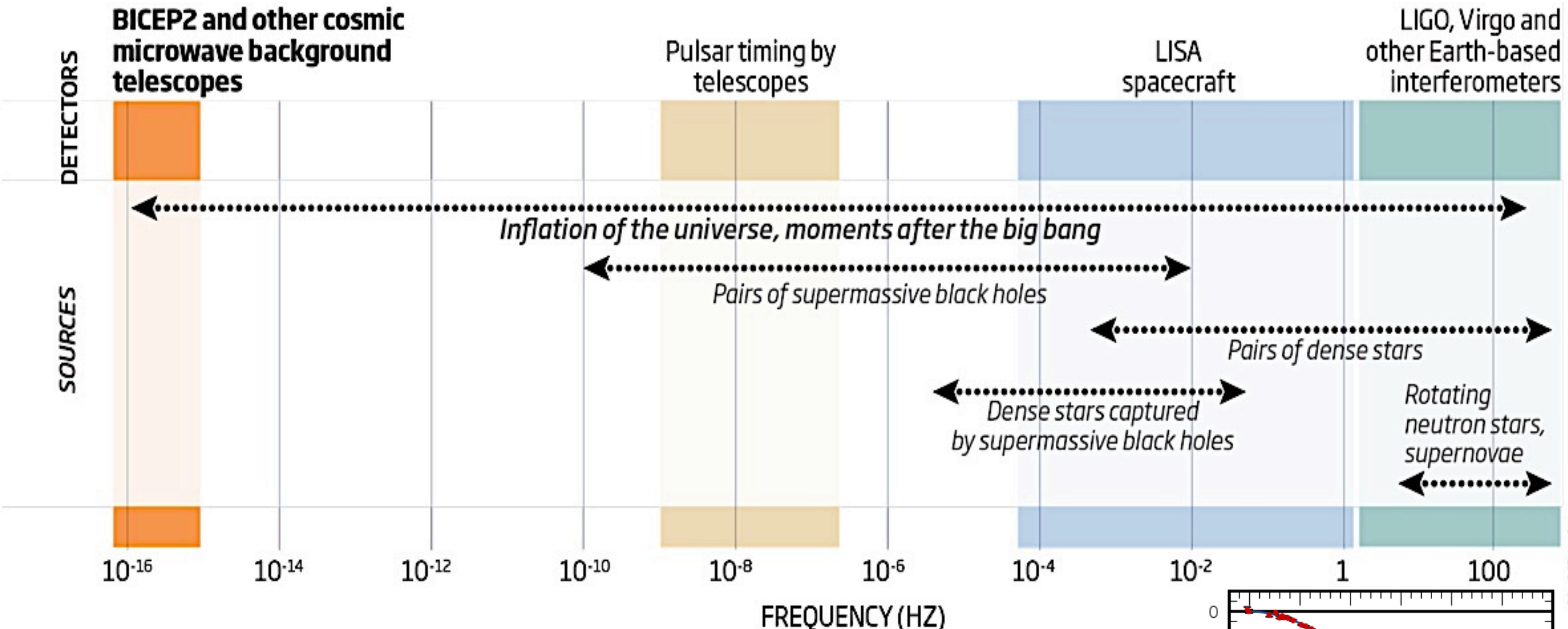


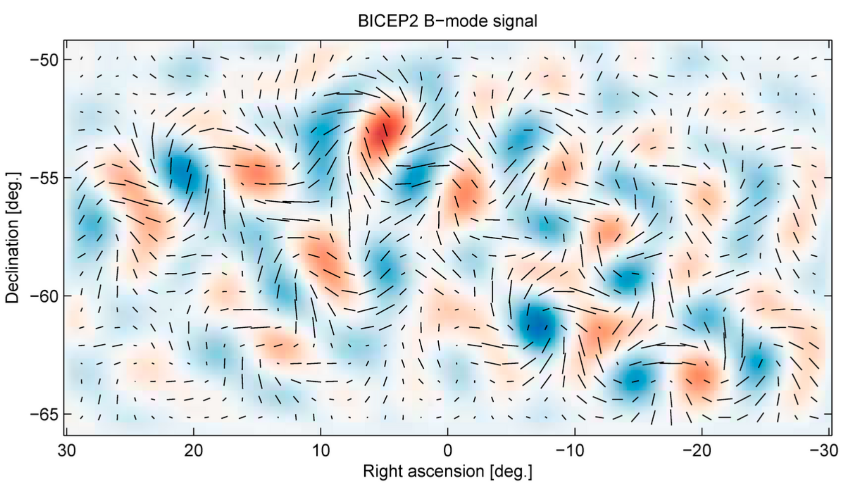
Gravitational Wave Astronomy

Ideal source for a wide range of GW detectors. Peak Luminosity **~ 10^{23} L_{Sun}**

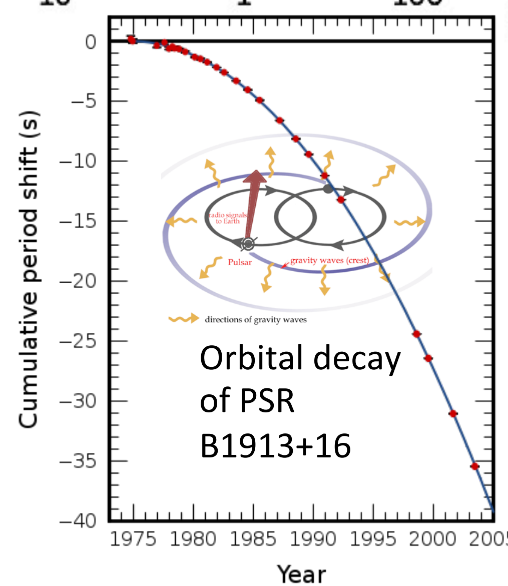


Gravitational Waves





indirect, evidence of GWs

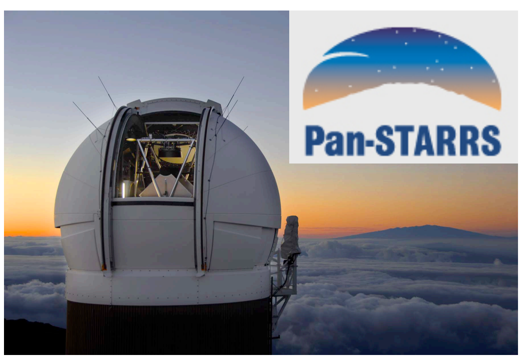


Multi-Messenger Astronomy

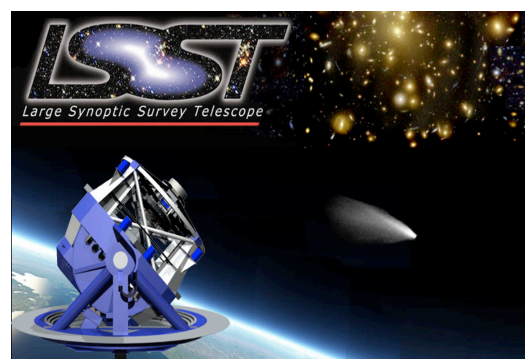
- **Combined GW and EM observations of close or merging BBH binaries could be the routine in a new kind of astronomy in the near future**

- Potential for coordinated GW-EM astronomy:
  - GW Detection/Localization ⟺ EM Detection/Localization
  - Distance vs Redshift ⇒ Cosmological Standard Sirens [Schutz 1986, Holz & Hughes 2005]
  - GW and EM signals can independently constrain different gravity models
  - Understanding of BH dynamics, merger scenarios, highly relativistic plasma, jet formation, etc

- High-cadence, all-sky survey astronomy data could differentiate EM signatures from SMBBH mergers from those of single AGNs in the near future



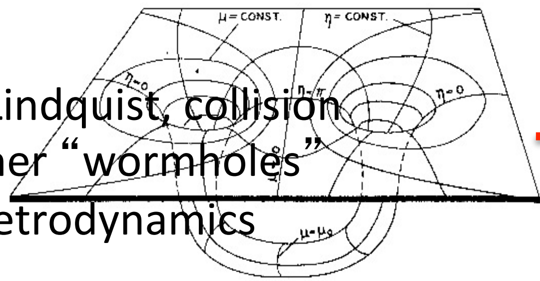
Pan-STARRS
2010-??
4 skies per month



Large Synoptic Survey Telescope (LSST)
2021-2032
1 sky every 3 days

It really took 50+ years of efforts …

There has been a worldwide ongoing effort since the 60's to do this "two body problem in GR

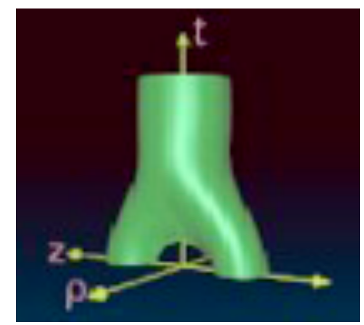


1960s — Hahn & Lindquist, collision of 2 Misner "wormholes" in Geometrodynamics

1970s — Smarr & Eppley, first head-on collision of 2 BHs, pioneering efforts on supercomputers at Livermore Natl Lab

1980s — Unruh' BH Excision, York' Formulation

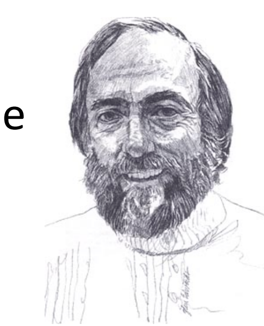
1990s — LIGO moves ahead, Grand Challenge, First 3D Code, Anninos et al, (Choptiuk critical phenomena)



2000s — Further attempts: Bona & Massó, Pitt-PSU-Texas AEI-Potsdam, Alcubierre et al. , PSU: first orbit Brügmann et al.

Codes Crash, NR is too difficult!

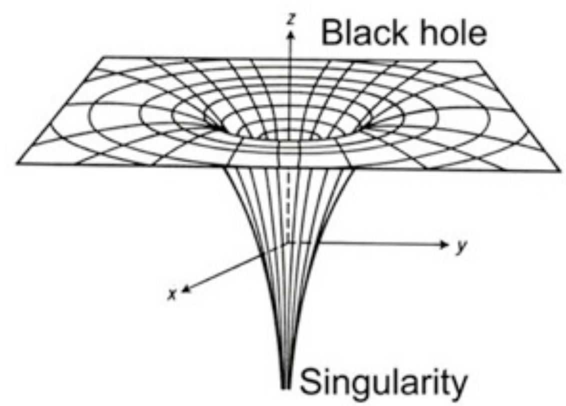
"I have bet these numerical relativists that gravitational waves will be detected from black-hole collisions before their computations are sophisticated enough to simulate them'' Kip S. Thorne, 2002



Views and Perspectives on this Problem

Shapiro and Teukolsky 1985:
"... **the Holy Grail of numerical relativity: a code that simultaneously avoids singularities, handles black holes, maintains high accuracy, and runs forever**."

- BHs are simple - described by mass and spin (and charge)!
- Just solve the ADM equations and run ...



- BHs are complicated - there is a physical singularity!
  - Excision
  - Punctures
- Einstein evolution equation change character depending on formulation and gauge

Why it took so long?

We did not have the appropriate package of Mathematical Tools (e.g. Gauges, Formulations) and Computational Infrastructure (e.g. Adaptive Mesh Refinements, Hardware, etc.)

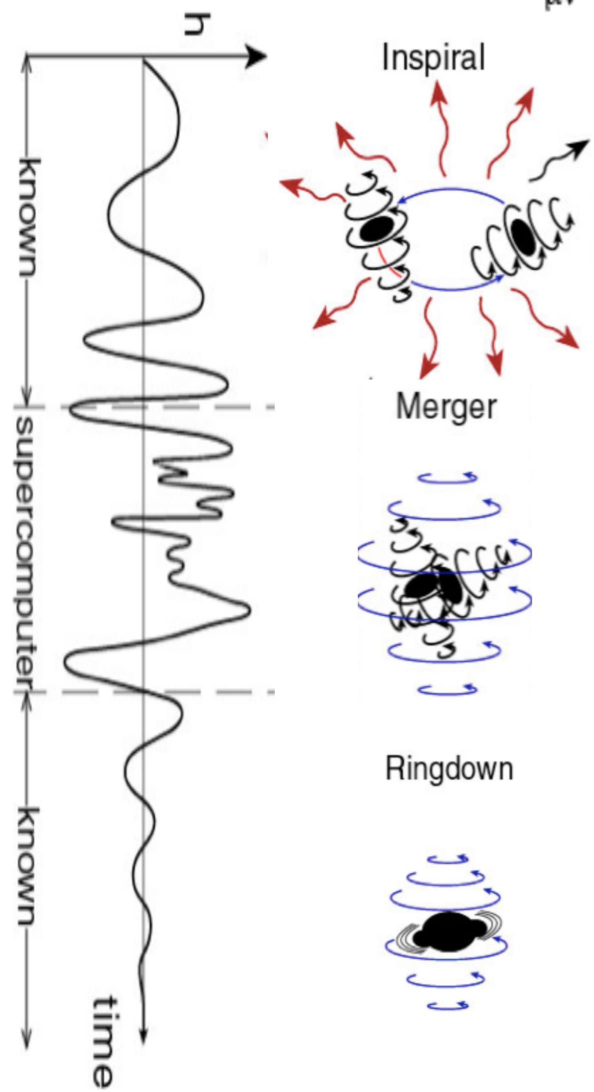
Binary Black Holes and Strong Field GR

Solve Field Equations of General Relativity: $G_{\mu\nu} = 8\pi\, T_{\mu\nu}$

Approximated with **post-Newtonian (PN)** models assume slow moving point particles

BHs move rapidly & the nature of the spacetime becomes important **Numerical Relativity (NR)** solves the full Einstein equations

Single Kerr **BH Perturbation theory** approximates



Mass ratio, orbital angular momentum, individual spins, eccentricity, separation (or orbital frequency)

Gravitational Waves

Recoil …

Final total mass and spin

Gravitational waveforms encode information about the BBH parameters …

The Moving Punctures Approach (eppur si muove)

Modified BSSN system (vacuum):

$$\partial_0 \tilde{\gamma}_{ij} = -2\alpha \tilde{A}_{ij},$$

$$\partial_t \chi = \frac{2}{3}\chi\left(\alpha K - \partial_a \beta^a\right) + \beta^i \partial_i \chi,$$

$$\partial_0 \tilde{A}_{ij} = \chi\left(-D_i D_j \alpha + \alpha R_{ij}\right)^{TF} + \alpha\left(K\tilde{A}_{ij} - 2\tilde{A}_{ik}\tilde{A}^k_j\right),$$

$$\partial_0 K = -D^i D_i \alpha + \alpha\left(\tilde{A}_{ij}\tilde{A}^{ij} + \frac{1}{3}K^2\right),$$

$$\partial_t \tilde{\Gamma}^i = \tilde{\gamma}^{jk}\partial_j\partial_k\beta^i + \frac{1}{3}\tilde{\gamma}^{ij}\partial_j\partial_k\beta^k + \beta^j\partial_j\tilde{\Gamma}^i - \tilde{\Gamma}^j\partial_j\beta^i + \frac{2}{3}\tilde{\Gamma}^i\partial_j\beta^j - 2\tilde{A}^{ij}\partial_j\alpha + 2\alpha\left(\tilde{\Gamma}^i{}_{jk}\tilde{A}^{jk} + 6\tilde{A}^{ij}\partial_j\phi - \frac{2}{3}\tilde{\gamma}^{ij}\partial_j K\right),$$

$$\tilde{\Gamma}^i = -\partial_j \tilde{\gamma}^{ij}.$$

$$\partial_0 = \partial_t - \mathcal{L}_\beta,$$

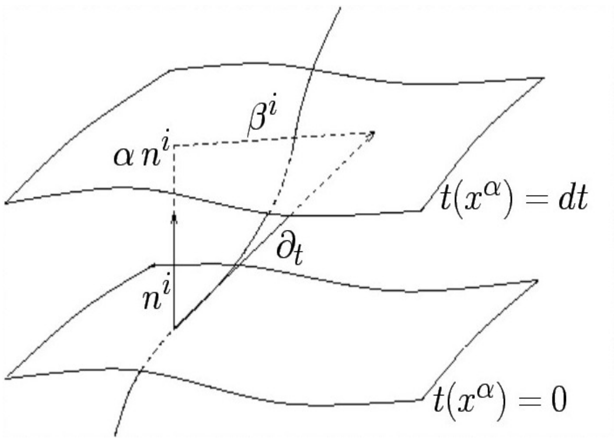
Dynamical Gauge:

Replace ϕ $(O(\log r))$ with $\chi = e^{-4\phi}$ $(O(r^4))$

$\partial_0 \alpha = -2\alpha K$

$\partial_t \beta^a = B^a$, $\partial_t B^a = 3/4\partial_t \tilde{\Gamma}^a - \eta B^a$

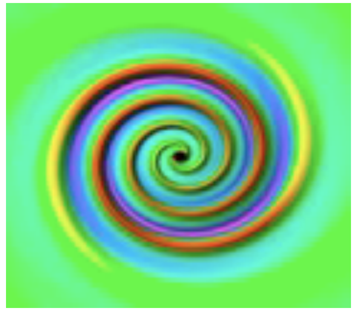
$\alpha(t=0) = \psi_{BL}^{-2} \qquad \beta^i = B^i = 0.$

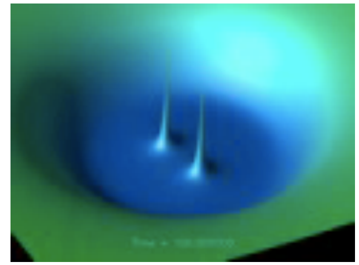


Computational horsepower

Binary Black Hole Problem "Solved"

2005 Pretorius
Binary inspiral and merger
Phys.Rev.Lett. 95 (2005) 121101



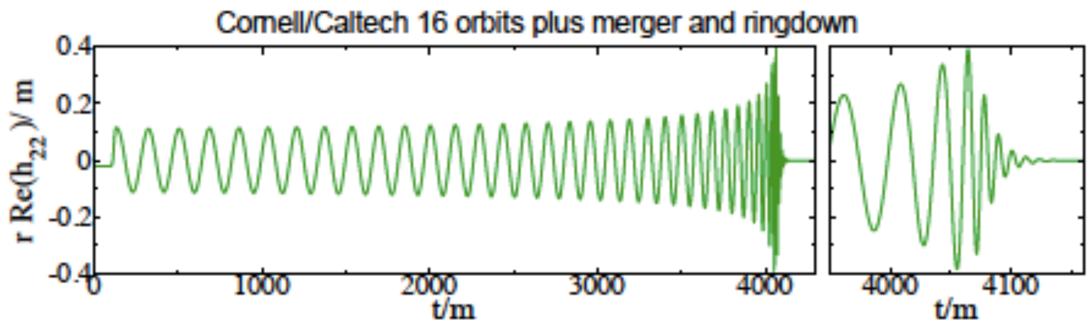


2005/2006 UTB/RIT and NASA
Moving Punctures Method
Campanelli, Lousto, Zlochower, Marronetti, Phys.Rev.Lett. 96 (2006) 111101
Baker, Centrella, Choi, Koppitz, van Meter, Phys.Rev.Lett. 96 (2006) 111102

GWs from the merger of two non-spinning, equal-mass BHs carry away 4% of their initial energy in roughly an orbital time, and leave behind a remnant BH spin parameter of 0.7

Today ~ 10 codes:

- Spectral Einstein Code (SpEC)
- Moving Punctures Codes



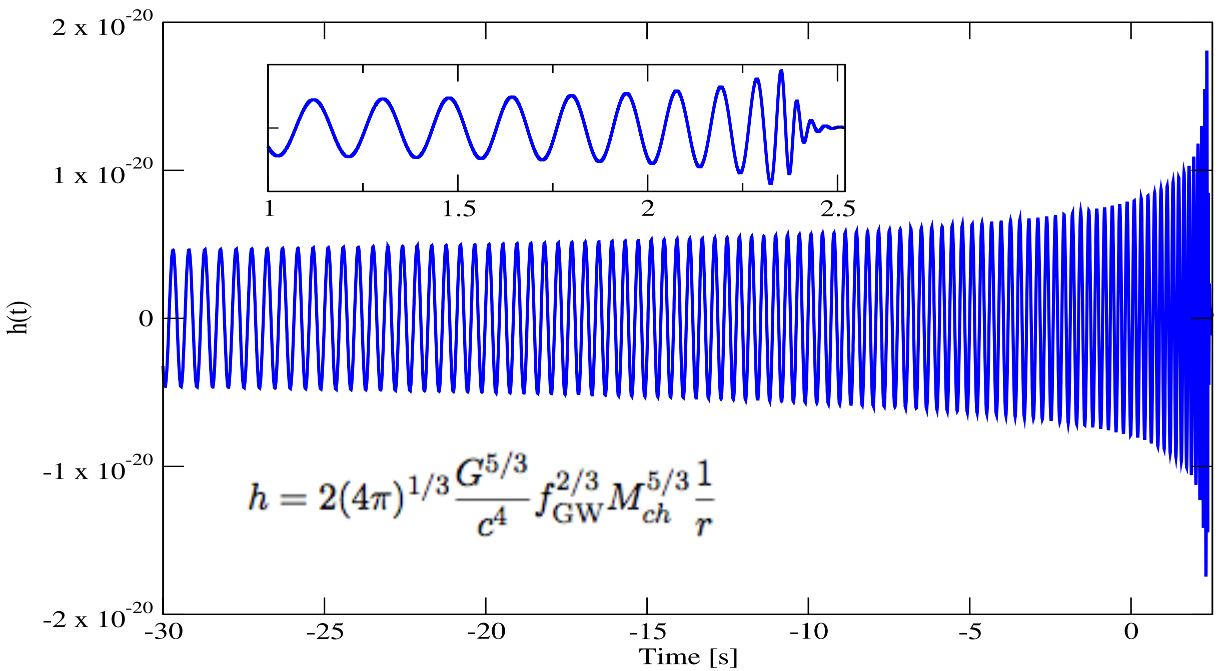
Courtesy Lee Lindblow

einstein toolkit

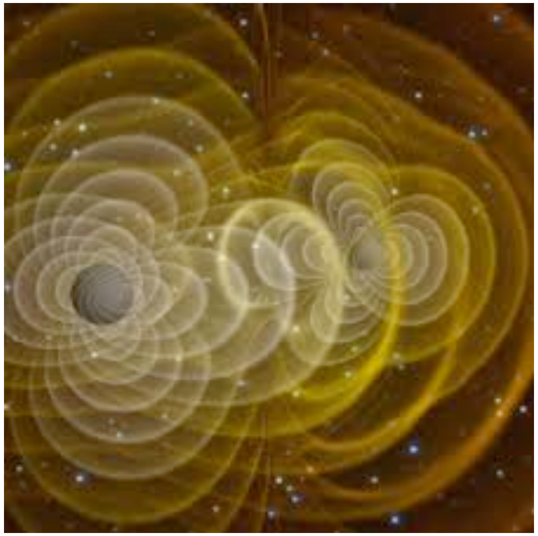
MPI Computational Toolkit (Cactus)
Adaptive mesh refinement (Carpet)
Computer algebra generation of numerical codes (Kranc)
Multipatch (Llama, ET)
GRMHD (GRHydro, Whisky)

Gravitational Waveforms

Waveforms are essential on assisting GW detectors, both to predict what to expect and to extract physical information about the BBH source



$$h = 2(4\pi)^{1/3}\frac{G^{5/3}}{c^4} f_{\rm GW}^{2/3} M_{ch}^{5/3}\frac{1}{r}$$



$$\psi_4(r,t,\theta,\phi) = \sum_{\ell m} \psi_{4\,\ell m}(r,t)\,{}_{-2}Y_{\ell m}(\theta,\phi)$$

$$\Psi_4 = \ddot{h}_+ - i\ddot{h}_\times$$

GR is scale invariant, so waveforms are independent of the total mass

Units: c = G = 1
→ 1 M ~ 5 x 10^{-6} (M/M_{Sun}) sec
~ 1.5 (M/M_{Sun}) km

The SpEC Catalog

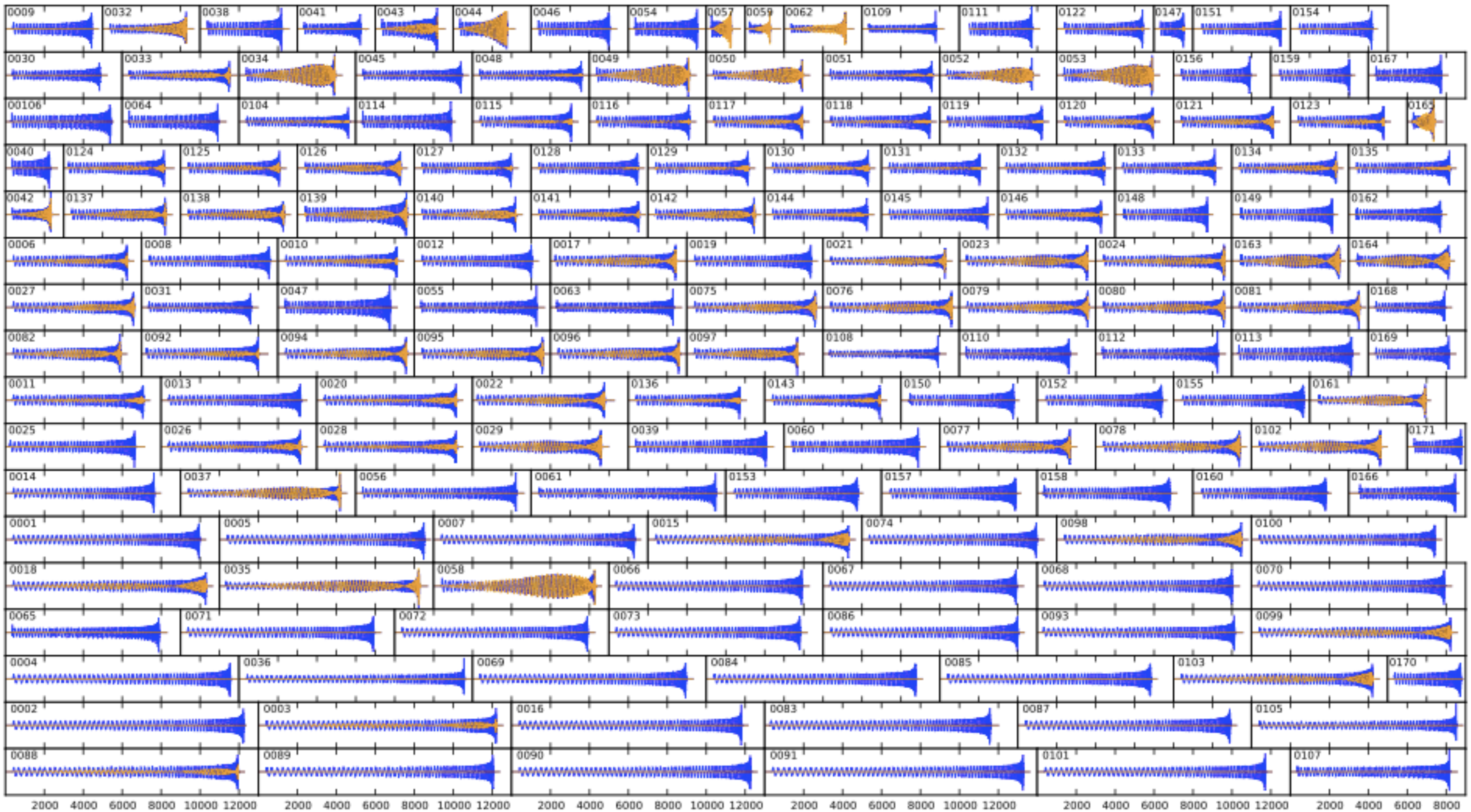


FIG. 3. Waveform polarizations h_+ (blue) and $h_\times$ (orange) in a sky direction parallel to the initial orbital plane of each simulation. All plots have the same horizontal scale, with each tick representing a time interval of $2000M$ (equal to 0.2 s for a $20M_\odot$ BBH).

Pfeiffer++ 2013

Merger of Spinning Black Holes: Hang-Up Orbits

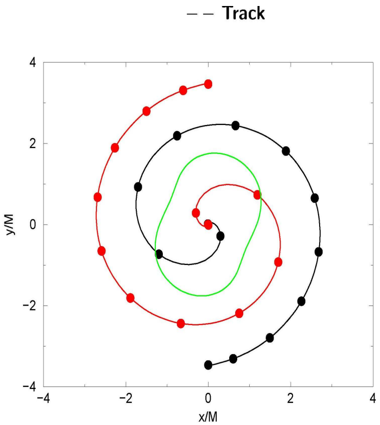


Figure 4: Puncture tracks for the – – configuration.

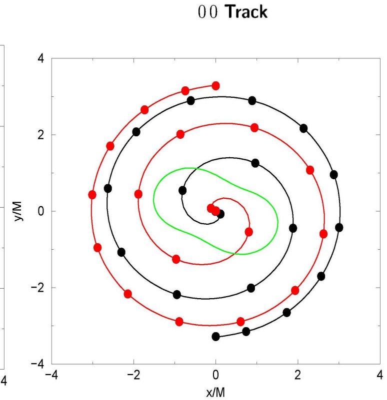


Figure 5: Puncture tracks for the 0 0 configuration.

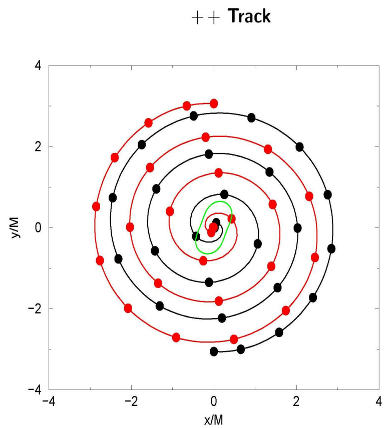
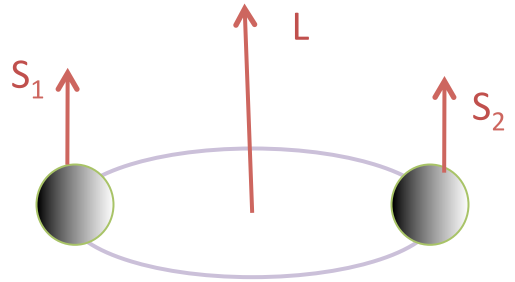
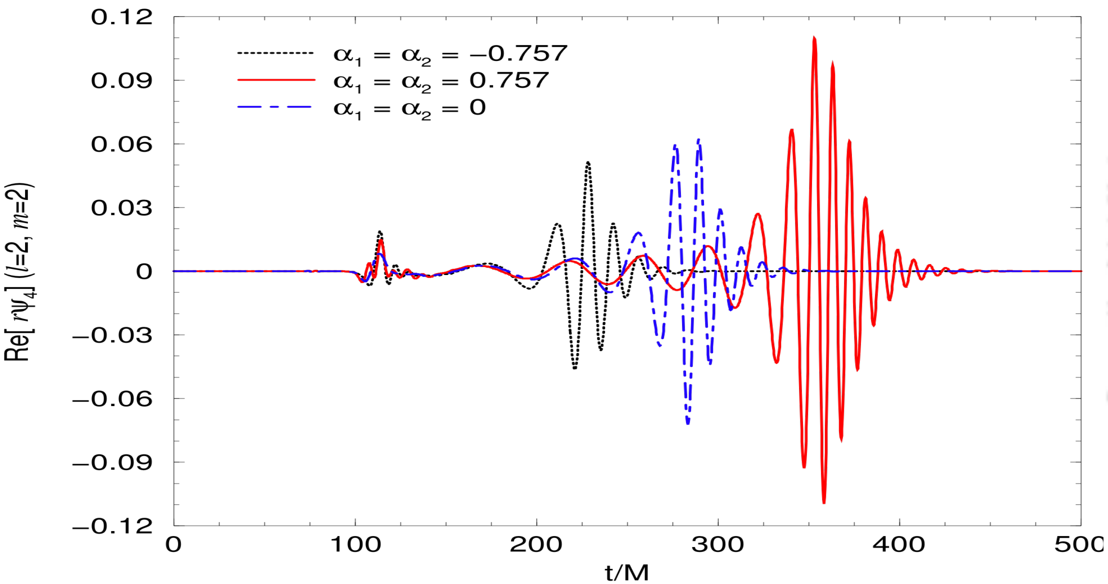


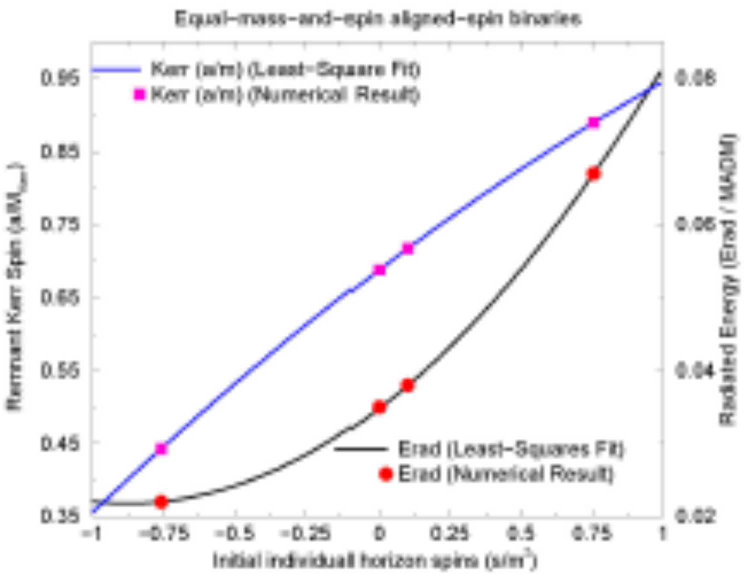
Figure 6: Puncture tracks for the + + configuration.



- Equal-mass BHBs
- $S_{1,2}/m^2 = \{-0.75, 0, 0.75\}$
- $M\Omega = 0.05$ (Starting "radius" the same).

• Hang-up effect due to repulsive spin-orbit interaction leaving behind a remnant with sub-maximal spin <0.96) [Campanelli, Lousto, Zlochower, PRD 2006]: cosmic censorship respected!

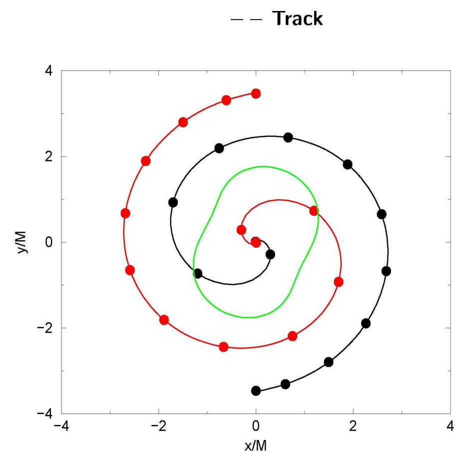




The High Spin Corner

Campanelli+, Phys Rev D, 2006

Orbital-hangup effect: When spins are aligned with L, repulsive spin-orbit coupling delays the merger, maximizing the amplitude of gravitational radiation, and leaving behind a submax Kerr BH (Cosmic censorship at work!)



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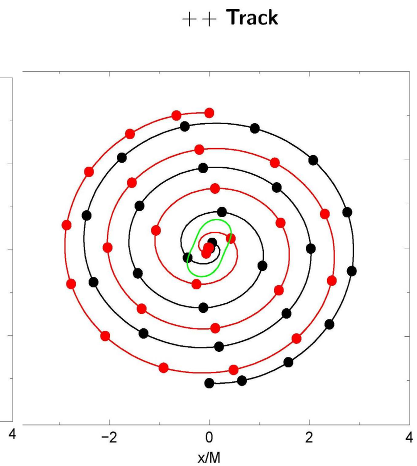

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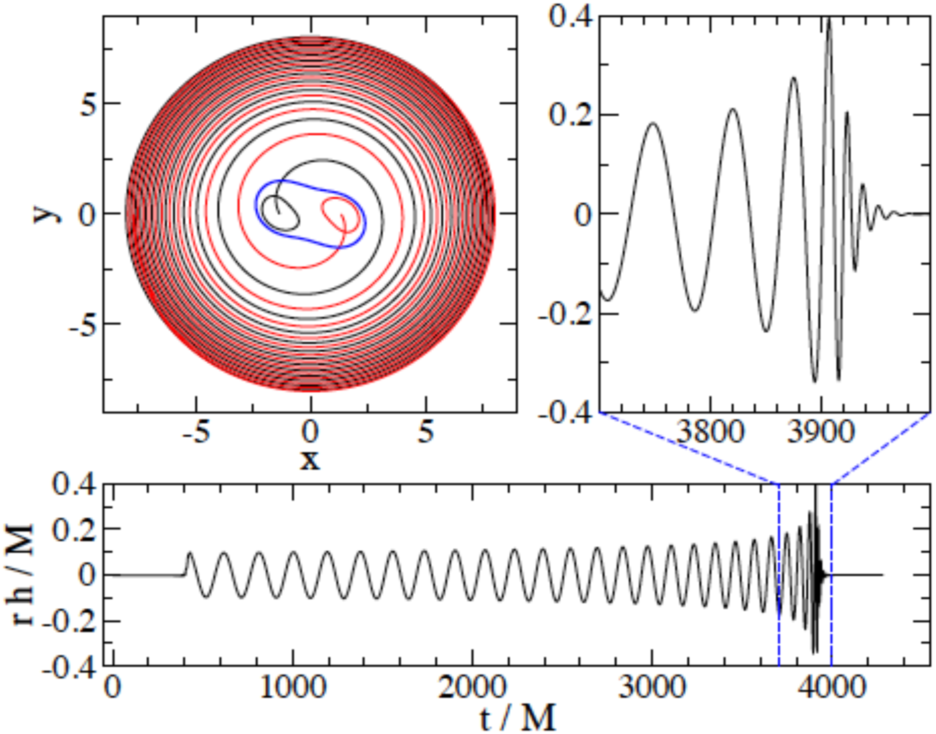
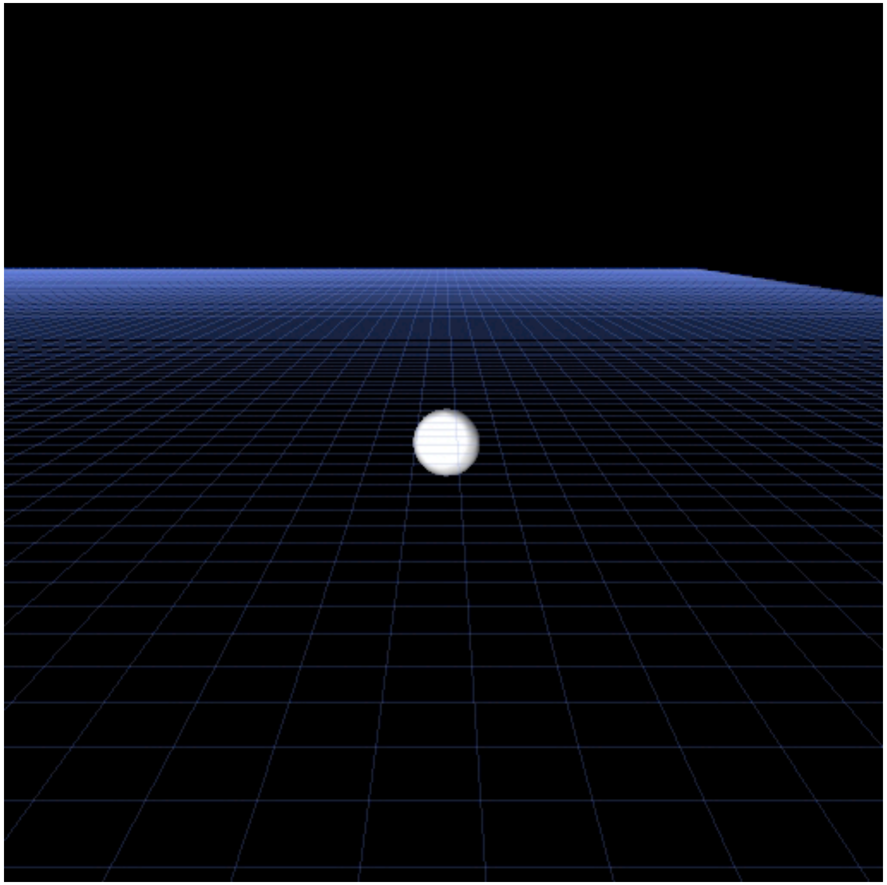
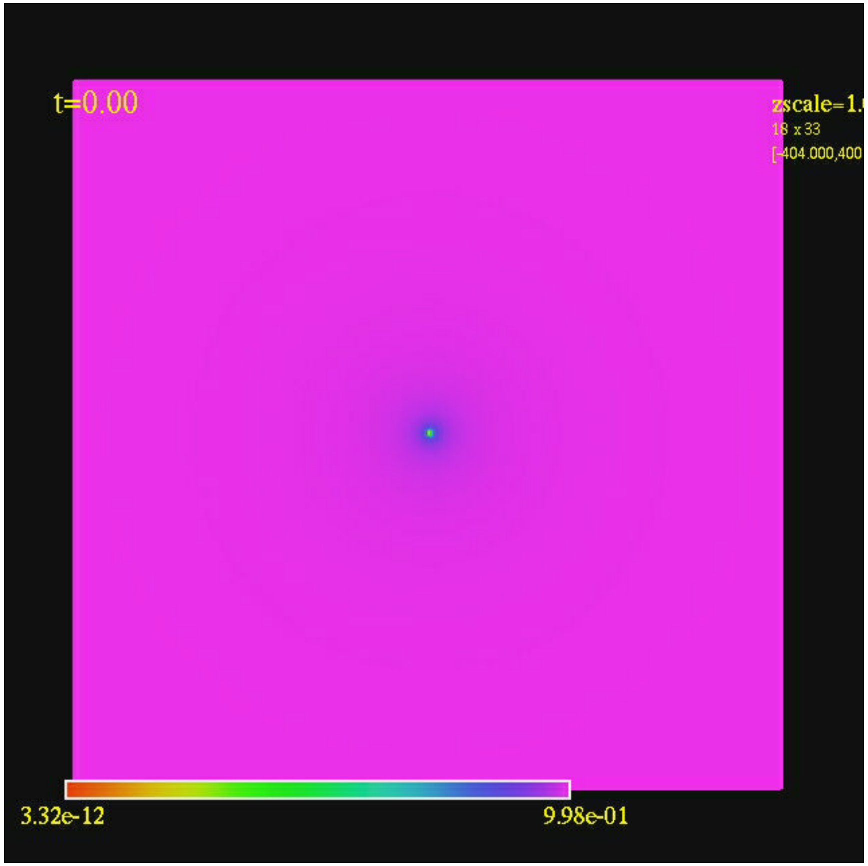


Lovelace+, Phys. Rev. D, 2011

Make a 12 orbits evolution of BBH with spins=0.97. Radiates over 10% of its mass in GW. The brightest source in the entire Universe!

Some Simulations are still very challenging!



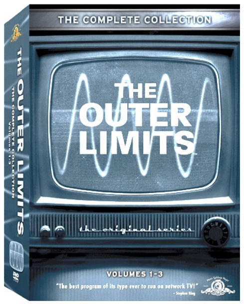


Lousto & Zlochower, Phys. Rev. Lett. 2011

Mass-ratio: 1/100

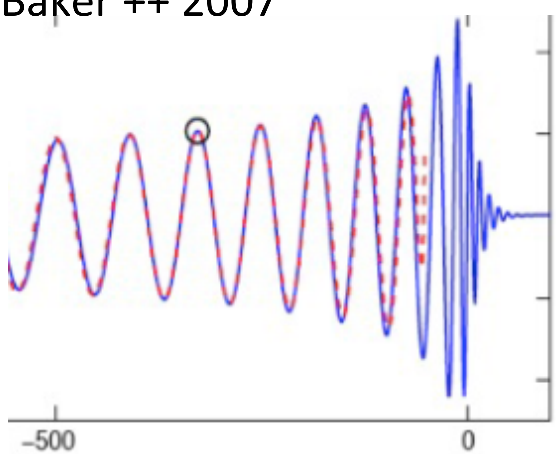
15 levels of refinements in AMR guided by BH perturbation theory, adapted gauge conditions

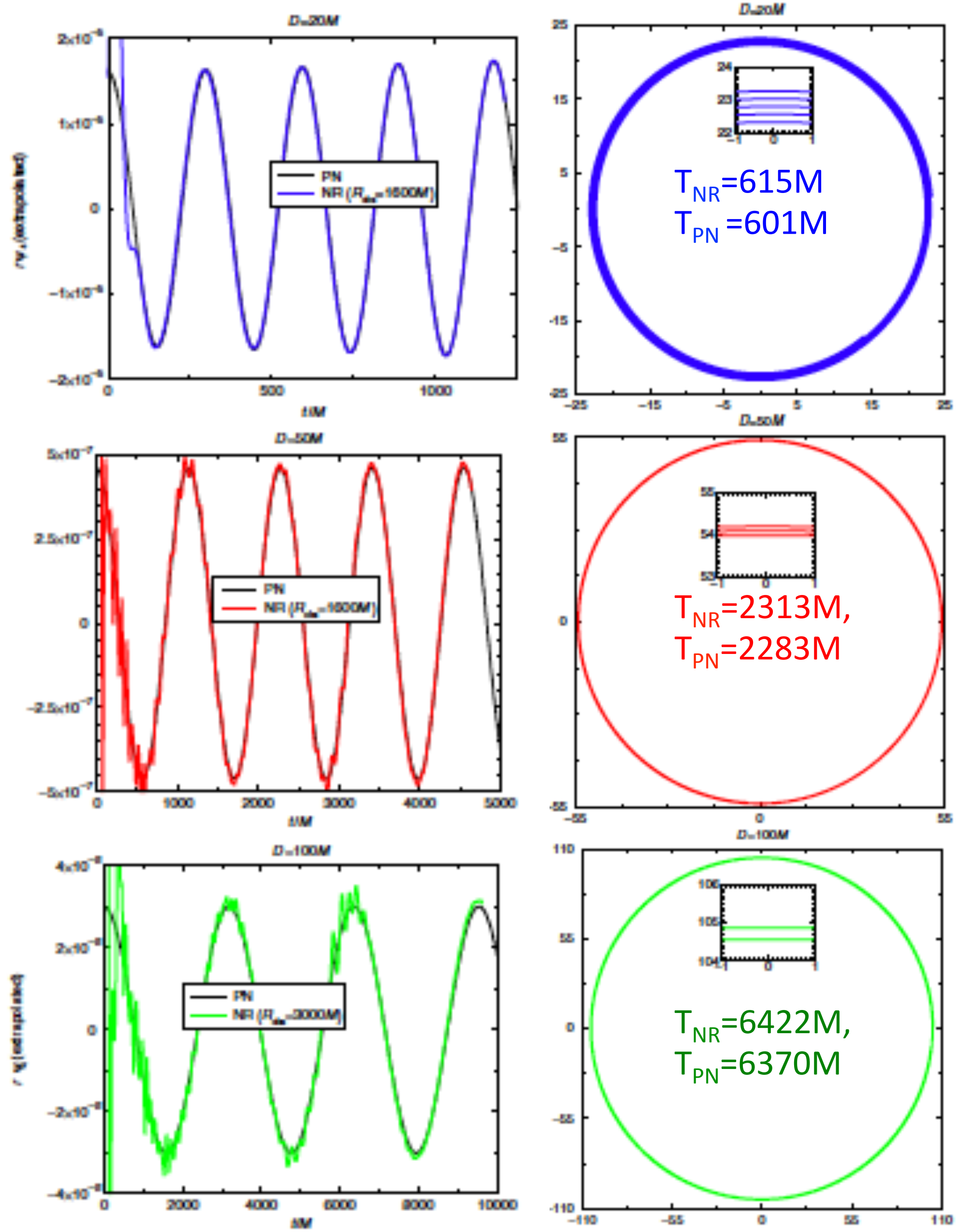
The Outer Limits of Black Hole Binaries



- Equal mass, non-spinning BBH show very good agreement with PN up to 100 M of separation
  Lousto & Zlochower, 2013

- Equal-mass, non-spinning comparisons agree up to 2-3 orbits before merger
  Baker ++ 2007



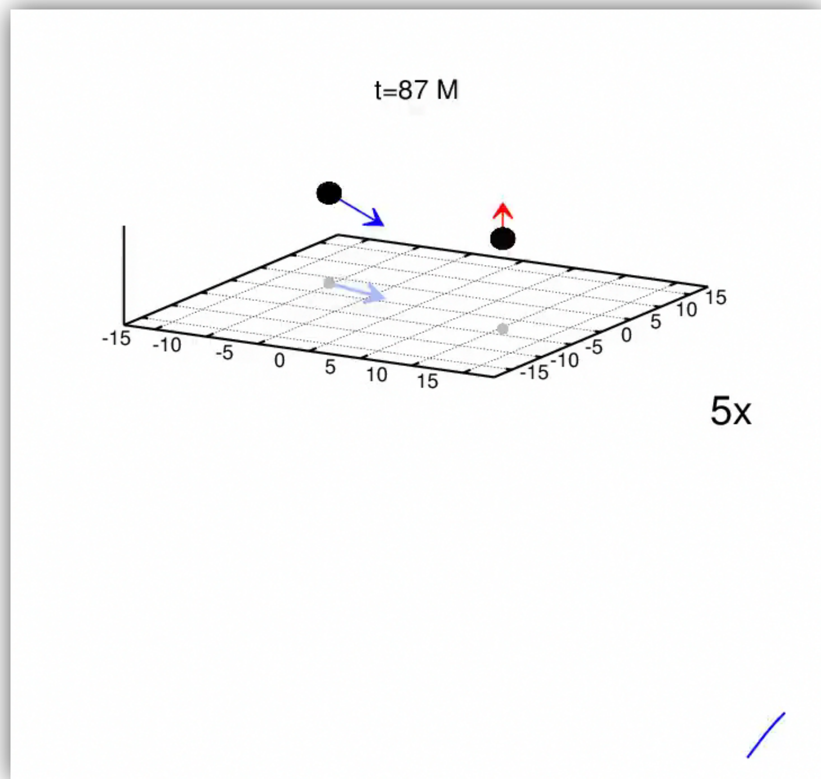


Spin Dynamics and Astrophysics: Spin Flip-Flop

Lousto & Healy, , Phys. Rev. Lett., 2015

For precessing BBH, the orientation of the spin of one of the BHs can reverse completely (spin flip-flop).

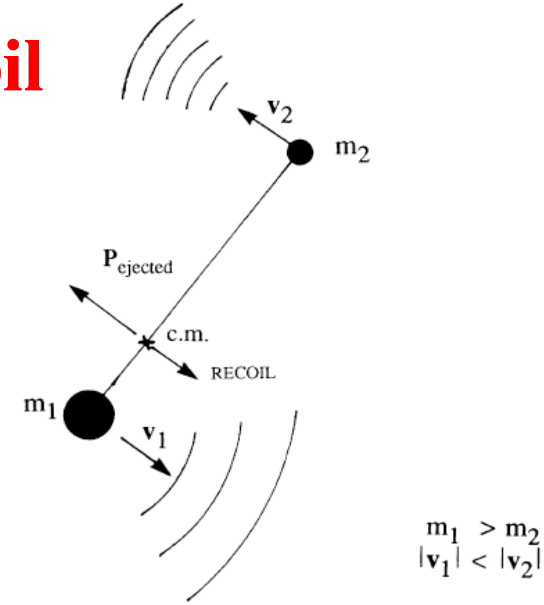
Verified with long NR simulation, but this is essentially a 2PN effect due to conservation of S•L = 0.



- The dynamical scale for the spin flip-flop is shorter than the GW timescale, so gas-driven alignment processes might be less effective than expected!

- This has consequences for accretion disk dynamics, and possible EM observations of inspiralling SMBBH …

Gravitational Radiation Recoil



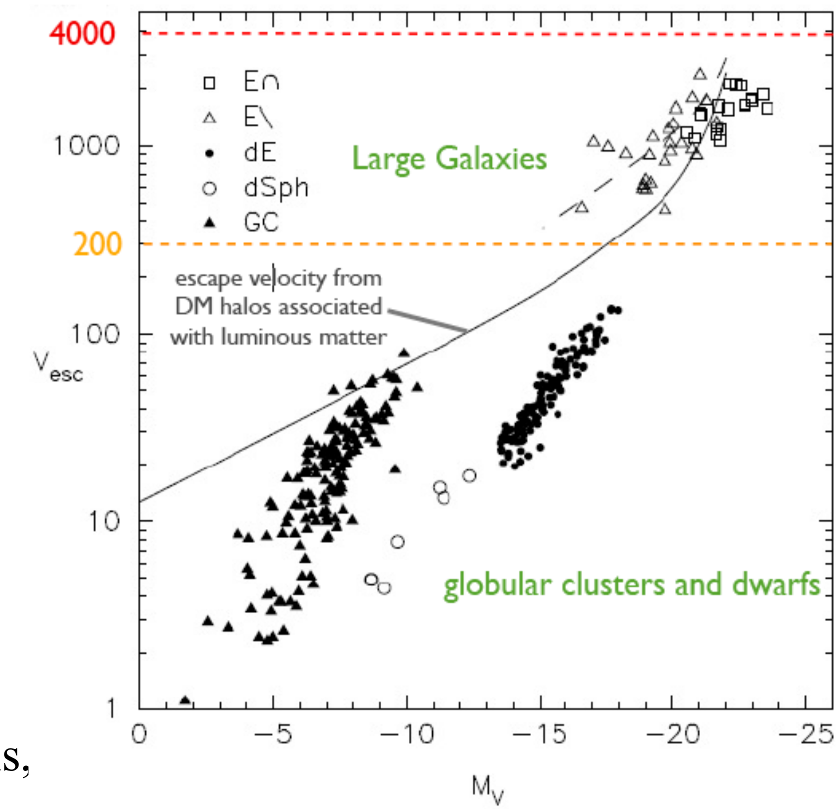
- In binary black-hole (BH) coalescences, asymmetrical gravitational radiation carries a net linear momentum, causing center-of-mass recoil. To conserve momentum the merged BH is given a kick in the opposite direction.

- The magnitude of the kick has an impact in astrophysics:
  - galactic population synthesis models
  - massive black hole formation scenarios

- If large enough (compared to escape velocity), the final BH remnant could be kicked out from the host structure …

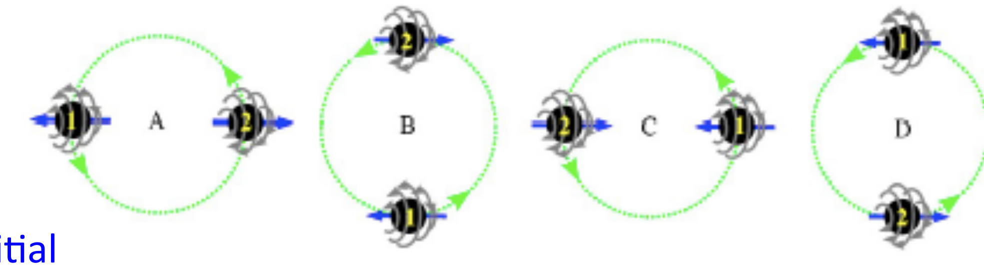
- Escape velocities:
  - < 100 km/so for globular clusters
  - ~ 500-1000 km/s for spiral galaxy bulges
  - ~ 2000 km/s for giant elliptical galaxies

- There are a number of possible observational consequences: off-set galactic nuclei, displaced active galactic nuclei, population of galaxies without SMBHs, x-rays afterglows, feedback trails,

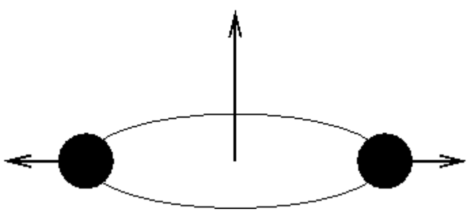


Super Large Kicks from Spinning BBH

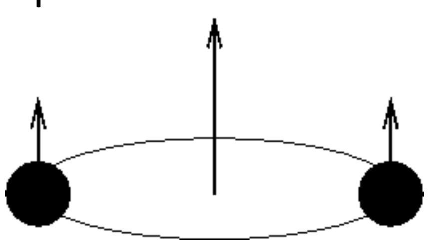
Superkicks v_{max} ~ 4000 km/s
Campanelli + 2007
González + 2007



Recoil velocity depends sinusoidally on the initial phase of the binary, and linearly (at leading order) on the spin magnitude (empirical formula).

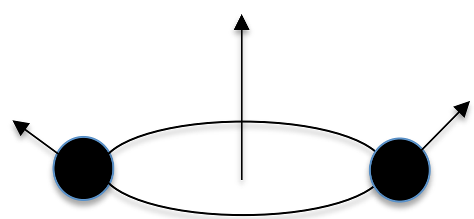


Moderate GW generation
Superkicks

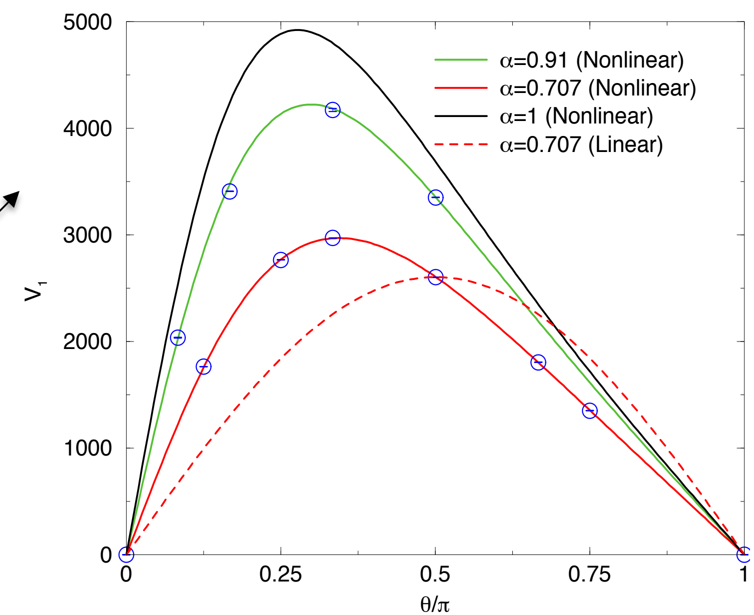


Strong GW generation
No kicks

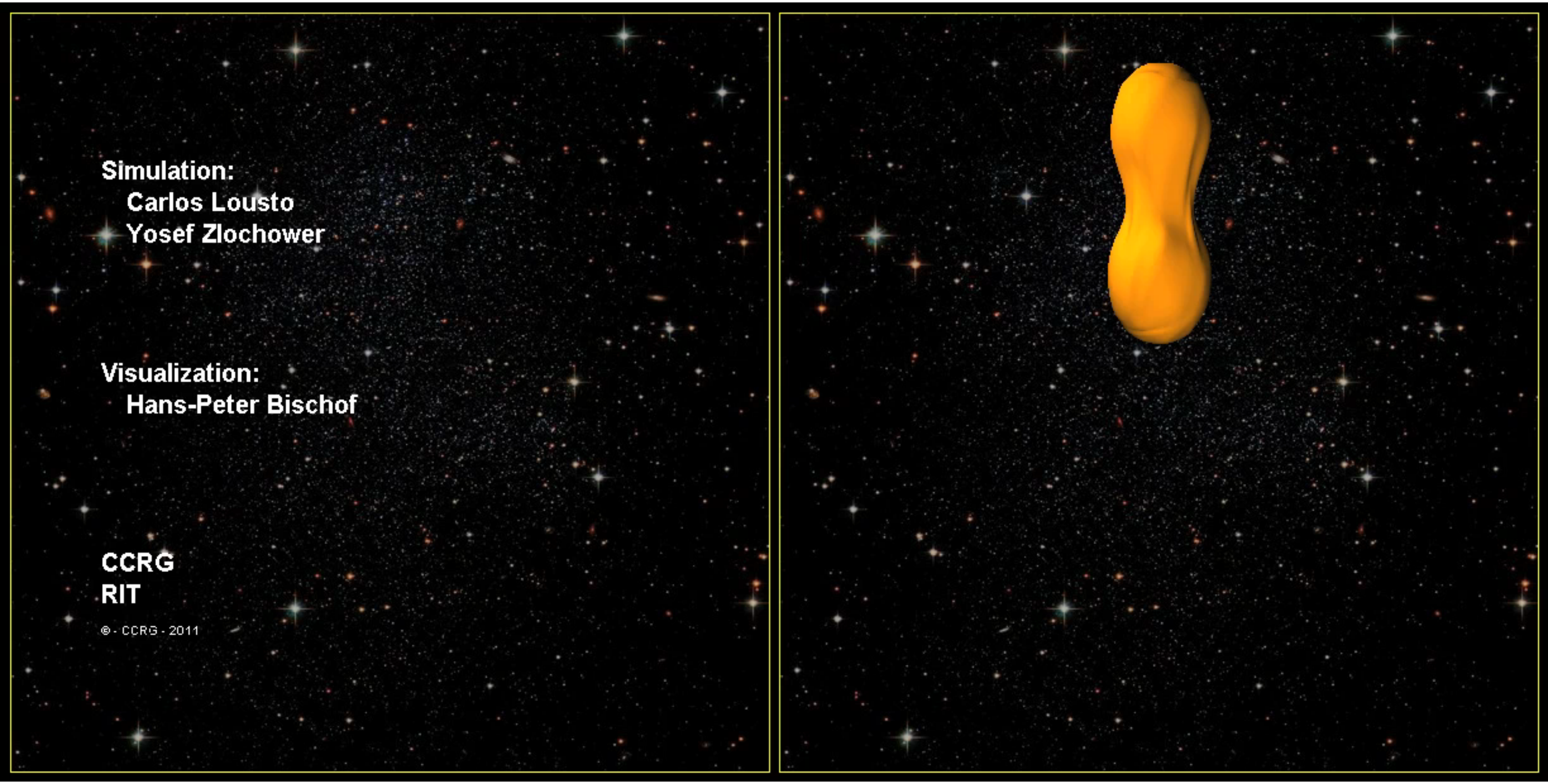
Hang-Up Kicks v_{max} ~ 5000 km/s
Lousto & Zlochower+ 2007



Hang-Up kicks



Hangup Kicks: The Movie

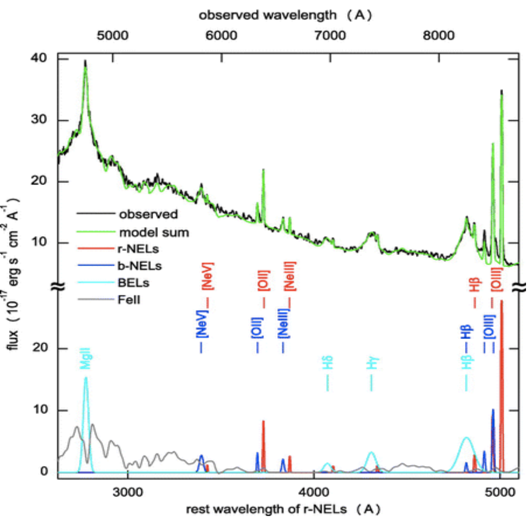


Hangup Kick (Left) and Radiated Power (Right)

BH Kicks as Post-Merger Signatures

- Recoiling BHs can retain a massive accretion disk. The disk will fuel a lasting QSO phase while the BH wanders far from the galactic nucleus.

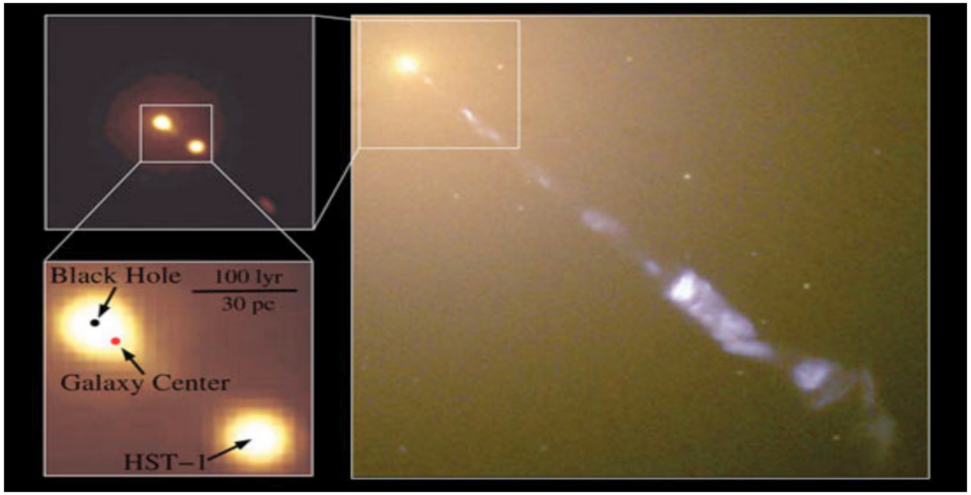
- There are relatively few observations of kick candidates:



- SDSS J0927 + 2943 [Komossa et al. 2008]
  - BLR (one set) shifted 2600 km/s; double picked NLR
  - Kick interpretation: blue system is kicked hole, with blue NLR due to expanding gas from edge of bound disk. Red NLR is in host galaxy ionized by kicked AGN.

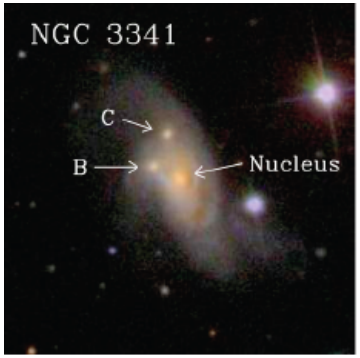
- More double-peaked emitters [Bonning et al, 2007; SDSSJ1050 Shields et al, 2009; Civano et al, 2010]

- Alternative interpretations: binary BHs, unusual NLR properties



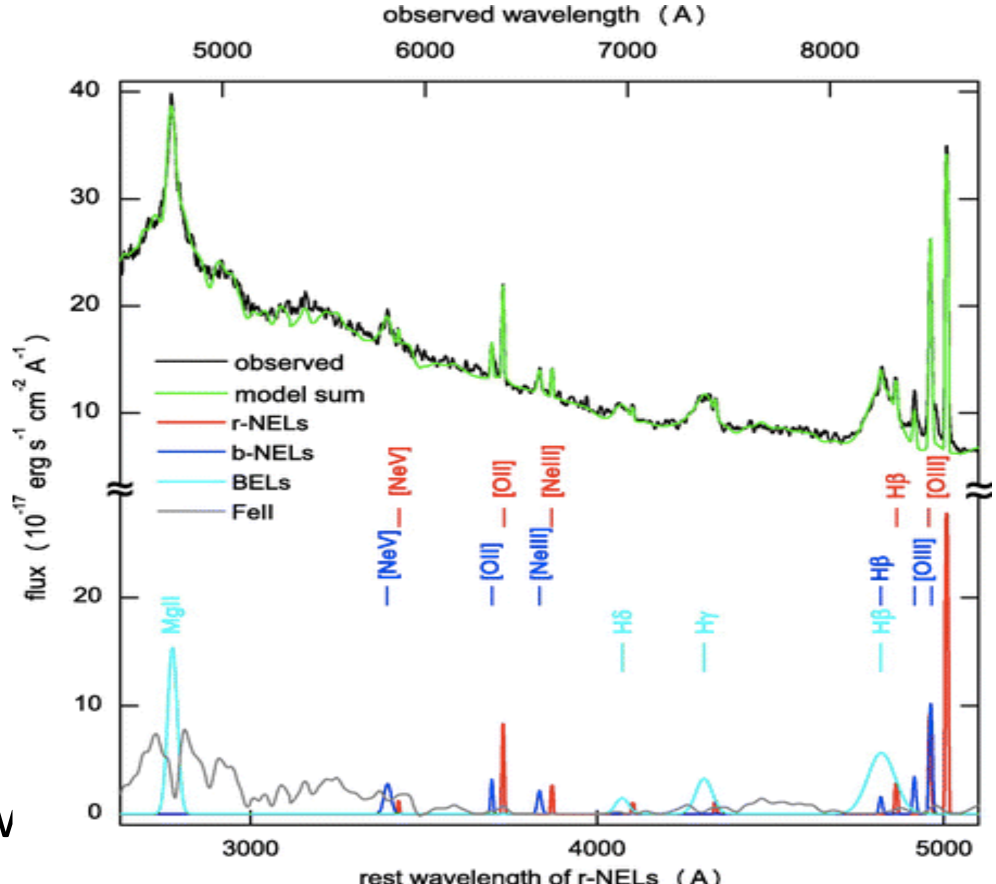
- HST image of a displaced SMBH in M87 [Batchelor et al, ApJL 2010]; Kick due postmerger ot jet?

- More off-set nuclei [Barth et al. 2008]



Observational evidence

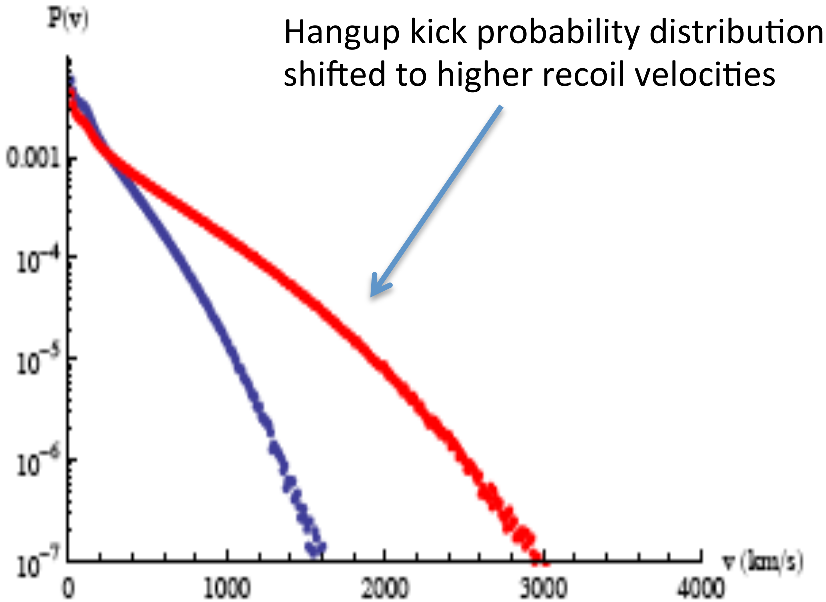
- Komossa et al (2008),
- Shield et al (2009),
- Civano et al (2010)
- Surveys
  - Eracleous et al (2011)
    - DV>1000km/s. 88 objects,
    - 68 spectra -14 binaries
  - Tsalmantza et al (2011)
    - SDSS, 32 objects -9 binaries
- Komossa (2012) compact review



This observations could well be the first confirmation of highly dynamic, nonlinear (strong field), predictions of GR (NR)!

Probabilities to Observe Large Recoils

Partial alignment of the spins by gas accretion cannot inhibit large recoils as conjectured in [Bogdanovic+07), Dotti +10)]



Spin distribution: $P(x) \propto (1-x)^{(b-1)} x^{(a-1)}$

Mass distribution: $P(q) \propto q^{-0.3}(1-q)$

Feed this to recoil velocity formula and calculate the recoil distribution (table).

Probabilities that remnant BH recoils in any direction from host structure (spins from SPH simulations of hot and cold accretion models) [Lousto+12]:

- 0.02% for galaxies with v_{esc} ~ 2500 km/s
- 5% for galaxies with v_{esc} ~1000 km/s
- 20% for galaxies with v_{esc} ~500 km/s

For the hot case, there is a nontrivial probability of observing a recoil larger than 2000 km/s, but for cold disks, such recoils are suppressed.

Vel. (km s^{-1})	(Hot)	Obs. (Hot)	(Cold)	Obs. (Cold)
0-100	34.2593 %	60.1847 %	41.4482 %	71.2967 %
100-200	21.1364 %	16.9736 %	28.3502 %	16.8471 %
200-300	11.6901 %	8.1110 %	12.503 %	6.1508 %
300-400	7.8400 %	4.8108 %	7.0967 %	2.8281 %
400-500	5.7590 %	3.0913 %	4.2490 %	1.3973 %
500-1000	14.0283 %	5.6593 %	5.9309 %	1.4258 %
1000-1500	4.0183 %	0.9809 %	0.4030 %	0.0526 %
1500-2000	1.0309 %	0.1638 %	0.0185 %	0.0015 %
2000-2500	0.2047 %	0.0223 %	0.0005 %	2×10^{-5}%
2500-3000	0.0296 %	0.0023 %	1×10^{-5}%	0.%
3000-3500	0.0032 %	0.0002 %	0. %	0.%
3500-4000	0.0002 %	$4. \times 10^{-6}$ %	0.% %	0.%

Summary and Conclusions

The field of "BBH mergers" progressed tremendously in the last 10 years and have already made some amazing predictions:

- BBH mergers radiate up to 12% of total mass (depending on spin)
- Many efforts to calculate waveforms to support GW efforts underway, and now tackling most extreme BBH cases
- BBH merger remnants can recoil at up to 5 000 km/s
  - B/N lines, galaxy core displacement, disturbance velocity star field
  - Difficult to grow IMBH and in globular clusters
  - May affect light/heavy seeds to grow structure in the universe
- There could be distinguishable light signatures due to MHD accretion in strong dynamical GR (characteristic variability, jet production, etc).
- Multi-messenger astronomy with BBH is at our doorstep!

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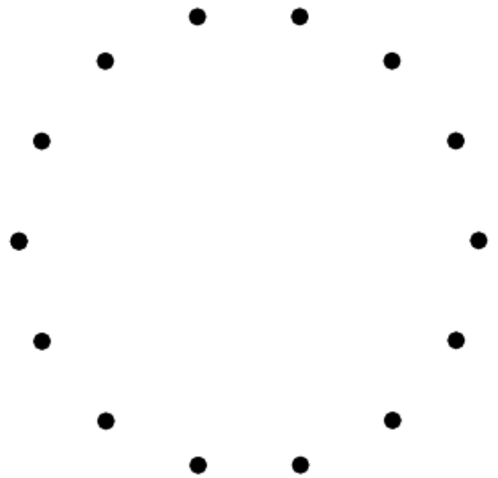
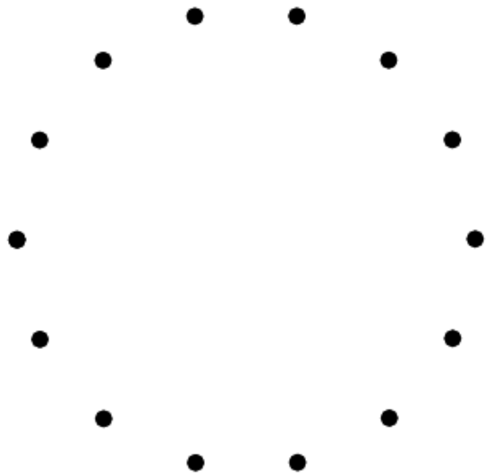
Modes of polarization of gravitational waves



Plus polarization



Cross polarization